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GASEOUS EXHAUST EMISSIONS FROM A JT8D-109 TURBOFAN ENGINE AT SIMULATED CRUISE FLIGHT CONDITIONS

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16. Abstract

Gaseous emissions from a JT8D-109 turbofan engine were measured in an altitude facility at four simulated cruise flight conditions: Mach 0.8 at altitudes of 9.1, 10.7, and 12.2 km and Mach 0.9 at 10.7 km. Engine inlet-air temperature was held constant at 283 K for all tests. Emissions measurements were made at nominally 6-cm intervals across the horizontal diameter of the engine exhaust nozzle with a single-point traversing gas sample probe. Measured emissions of the oxides of nitrogen (NO_x) decreased with increasing altitude from an emission index of 10.4 to one of 8.3, while carbon monoxide increased with increasing altitude from an emission index of 1.6 to one of 4.4. Unburned hydrocarbon emissions were essentially negligible for all flight conditions. Since the engine inlet-air temperatures were not correctly simulated, the NO_x emission indices were corrected to true altitude conditions by using correlating parameters for changes in combustor inlet temperature, pressure, and temperature rise. The correction was small at the lowest altitude. At the 10.7- and 12.2-km, Mach 0.8 test conditions the correction decreased the measured values by 1 emission index.

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SUMMARY

Gaseous emissions from a JT8D-109 turbofan engine were measured in an altitude facility at four simulated cruise flight conditions: Mach 0.8 at altitudes of 9.1, 10.7, and 12.2 kilometers and Mach 0.9 at 10.7 kilometers. The engine tested is an experimental refanned version, but the combustor system is identical to JT8D-9 production engines. The engine inlet-air temperature was held constant at 283 K for all tests. Emissions measurements were made at nominally 6-centimeter intervals across the horizontal diameter of the engine exhaust nozzle with a single-point traversing gas sample probe.

Measured emissions of the oxides of nitrogen (NO_x) decreased with increasing altitude from an emission index of 10.4 to one of 8.3 over the range of conditions investigated. Since the engine inlet-air temperatures were not correctly simulated, the NO_x emission indices were corrected to true altitude conditions by using correlating parameters for changes in combustor inlet temperature, pressure, and temperature rise. As expected, the correction was largest for the flight conditions where the difference between the actual and tested inlet-air temperatures was greatest. The correction was small for the Mach 0.8, 9.1-kilometer conditions. At the 10.7- and 12.2-kilometer, Mach 0.8 test conditions the correction decreased the measured values by about 1 emission index. Carbon monoxide emissions increased with increasing altitude from an emission index of 1.6 to one of 4.4 over the range of altitudes investigated. Unburned hydrocarbon emissions were essentially negligible for all flight conditions.

Integrated average emission indices calculated from the core stream were in excellent agreement with those calculated from the entire exhaust (core plus fan). Measurements from the core alone were found to be sufficient to characterize engine emissions.

INTRODUCTION

This report presents experimental measurements of exhaust emissions related to the influence of current subsonic jet transports on the upper atmosphere. The data were obtained from altitude chamber tests of a JT8D-109 turbofan engine.

Previous turbojet and turbofan altitude emissions studies (refs. 1 to 7) have concentrated on afterburning engines for high-altitude supersonic cruise. A recent subsonic emissions study (ref. 8) tested a low-thrust general aviation turbofan. Concern over the effects of stratospheric and upper tropospheric pollution by current subsonic transports has been expressed in references 9 and 10. Emissions studies related to subsonic transport engines have been largely limited to sea-level conditions (ref. 11) because their primary concern has been the problem of emissions near airports. This report presents some of the first simulated cruise emissions data taken from a turbofan engine that is comparable to the engines used in present commercial aircraft. The JT8D-109 engine is an experimental refan modification being tested for engine performance and which was available for emissions testing. Since the combustor design and combustor inlet conditions were not affected by the refan modifications, emissions results should be representative of current JT8D series 7, 9, and 11 engines. The test conditions simulated subsonic flight ($0.8 \leq M \leq 0.9$) at altitudes from 9.1 to 12.2 kilometers. The engine inlet pressure was correctly simulated for each flight condition. However, sufficient refrigerated air capacity did not exist for correct temperature simulation. Therefore, all tests were run with an engine inlet-air temperature of 283 K. Tests were conducted in the Propulsion Systems Laboratory at the Lewis Research Center. American Society for Testing Materials (ASTM) Jet-A aviation turbine fuel was used for all tests. Exhaust gas samples were obtained with a single-point traversing probe and were continuously analyzed for oxides of nitrogen, unburned hydrocarbons, carbon monoxide, and carbon dioxide.

APPARATUS

Engine and Facility

The JT8D-109 is an experimental engine developed under the NASA Refan Program. The basic JT8D-9, a turbofan engine, was modified by replacing the current fan with a design that provided increased engine bypass airflow to decrease jet noise and acoustic treatment to reduce fan noise. Two features essential to this emissions study are that this engine uses the current JT8D combustor system and that the compressor system is designed to provide combustor inlet conditions identical to the current JT8D engine. Therefore, the emissions results presented herein should be representative of current

JT8D series 7, 9, and 11 engines. Additional details of this engine may be found in reference 12.

Testing was conducted in the Propulsion Systems Laboratory at the Lewis Research Center. The engine was instrumented to record and monitor the engine operating parameters. These data and the emissions measurements were recorded by the facility digital data acquisition system. On-line computational capability provided rapid data reduction.

Gas Sampling Probe and Transport System

A single-point, traversing, water-cooled gas sampling probe was used to obtain emissions measurements. The probe and its traversing mechanism are shown mounted behind an engine in figure 1(a). The traversing mechanism had the capability to translate the probe ±60 centimeters horizontally and ±20 centimeters vertically from the engine centerline.

The sensor area of the probe is shown in figure 1(b). A schematic drawing of the sampling probe and a flow diagram of the gas analysis system are shown in figure 2. A total pressure sensor was mounted 2.5 centimeters above the sampling probe, and three unshielded Chromel-Alumel thermocouples were mounted 2.5 and 5 centimeters below and 5 centimeters above the gas sampling probe. The probe inlet had an inside diameter of 0.717 centimeter. The probe tip extended 1.9 centimeters forward of the rake body. This section was water cooled for a distance of 8 centimeters downstream from the tip. Following this section, the sampling line increased to 0.818-centimeter inside diameter. Thermocouples internal to the probe monitored the gas sample temperature to ensure that proper sample temperature was maintained. Approximately 10 meters of 0.95-centimeter-diameter stainless-steel line were used to transport the sample to the analyzers. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was heated with steam at 428 K. Four heated metal bellows pumps (two pumps in series in each of two parallel legs) were used to supply sufficient gas sample pressure, 17 N/cm^2, to operate the analytical instruments. The gas sampling line residence time was less than 2 seconds for all test conditions.

Gas Analysis Instrumentation

The exhaust gas analysis system consists of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to the visual readout at the console, electrical inputs are provided to the facility computer for on-line analysis and data evaluation.

The hydrocarbon (THC) content of the exhaust gas was measured with a Beckman Instruments Model 402 Hydrocarbon Analyzer. This instrument is of the flame ionization detector type. The concentration of the oxides of nitrogen (NO_x) was measured with a Thermo Electron Corporation Model 10A Chemiluminescence Analyzer. This instrument includes a thermal converter to reduce nitrogen dioxide (NO_2) to nitric oxide (NO). Data were obtained as total NO_x ($NO + NO_2$). Both carbon monoxide (CO) and carbon dioxide (CO_2) were measured with analyzers of the nondispersive infrared (NDIR) type. These instruments were Beckman Instruments Model 315B.

TEST CONDITIONS AND PROCEDURES

The engine test conditions are presented in table I. At each test condition, the engine power level corresponded to nominal cruise power as specified by the engine manufacturer.

Flight speeds and altitudes were simulated by setting appropriate engine inlet and altitude exhaust pressures. Sufficient refrigerated air capacity was not available for correct inlet-air temperature simulation at the higher altitudes. Therefore, engine inlet-air temperature was held constant at 283 K.

Sampling traverses were made approximately 25 centimeters downstream of the nozzle exit plane. Data were obtained at 6-centimeter (nominal) intervals across the horizontal diameter of the exhaust nozzle, resulting in approximately 16 data points per traverse. All gas analysis instruments were checked for zero and span prior to each traverse. Because the console allows rapid selection of zero, span, or sample modes, these frequent checks could be made during altitude changes while the engine was running.

Concentrations which were measured on a dry basis (NO_x, CO, and CO_2) are reported on a wet basis, correcting for water vapor including both inlet-air humidity and water vapor from combustion. Emission levels of all constituents were converted to emission index parameters, defined as grams of pollutant per kilogram of fuel. The local (gas sample) fuel-air ratio was calculated from the carbon-containing emissions. All calculations follow the Society of Automotive Engineers (SAE) recommended procedure (ref. 13).

RESULTS AND DISCUSSION

Traverse Profiles

The profile data obtained during the test program are presented in figures 3 to 7. The horizontal axis on the figures is the radial distance from the engine centerline nondimensionalized by the exit radius R_8, which is 49.5 centimeters.

Temperatures. - Measured exhaust total temperatures are shown in figure 3. The temperature profile clearly defines the core region of this mixed-flow (core plus fan) stream. Each data point shown is the average of the readings from the three thermocouples. While only the single test condition of 9.1-kilometer altitude at Mach 0.8 is shown, the temperature profiles obtained at all test conditions agree within a few degrees.

Local fuel-air ratio. - The local fuel-air ratios calculated from the gas sample measurements are shown in figure 4 for the 9.1-kilometer-altitude, Mach 0.8 case. This profile agrees very well with the temperature profile shown in the previous figure as far as defining the location of the core flow - fan flow interface. The shape of the radial profile of figure 4 arises as a consequence of the annular flow from the turbine and the exit temperature profile of the combustor.

The location of the centerbody wake can be seen from the total pressure profile in figure 5. The curve is discontinuous near the centerline because the interpolated pressure at the centerline may be well below the range of the plot.

Unburned hydrocarbon emissions. - The level of unburned hydrocarbons was less than 15 ppmC (parts per million of carbon by volume) for all conditions tested. Some problems were encountered with sample-line contamination where the background levels were equal to or greater than the hydrocarbon emissions. Consequently, 15 ppm represents an upper limit.

Carbon monoxide emissions. - Carbon monoxide concentration profiles are shown in figure 6 in parts per million by volume (ppmv) for each of the conditions tested. The overall level is quite low and, therefore, the radial variations within the core region are not significant. The trend of increasing CO concentration with increasing altitude is consistent with decreasing combustor pressure (table I).

Oxides-of-nitrogen emissions. - In addition to temperature, pressure, and residence time, the production of NO_x is dependent on the water content (humidity) of the air. As proposed in reference 14, NO_x data may be corrected to zero humidity by multiplying by the factor e^{19H}, where H is grams of water per gram of air. For these tests, the engine inlet air had a humidity of 0.0008 gram of water per gram of air, giving a humidity correction of less than 1.5 percent.

The volumetric exhaust concentration profiles of NO_x are shown in figure 7. The values shown are total NO_x ($NO + NO_2$). For several test conditions, a duplicate analyzer monitored NO. The measured ratio of NO to NO_x was 0.95 or greater. The trend of decreasing NO_x concentration with increasing altitude results from decreasing combustor pressure (table I).

Emission Indices

A previous analysis of sea-level emissions measurements on JT8D engines (ref. 15) showed considerable data scatter. This may be indicative of the difficulty of obtaining emissions data in a mixed-flow (core plus fan) exhaust stream since concentrations are encountered which are below the resolution of the instrumentation. Because of this scatter in the reference 15 data, several data reduction methods were used in the present study to evaluate differences that might have been observed if sampling had been confined solely to the core region.

The individual pressure, temperature, and species concentrations were used to obtain integrated average mass-weighted species concentrations. These average concentrations were used to calculate the emission-based fuel-air ratio and emission indices by the procedures of reference 13. The area of integration was varied to determine its effect on the value of the emission index. For the first data reduction method, the integration was carried out over the total nozzle diameter ($-1.0 \leq R/R_8 \leq 1.0$). For the second method, an integration area corresponding to the core diameter was chosen ($-0.6 \leq R/R_8 \leq 0.6$).

A third method, used by Lyon and others of General Electric (AF Contract F 33615-73-C-2047) was also evaluated. This method assumes that, if reactions are complete in the exhaust stream, a plot of local species concentration against local CO_2 concentration for any species of interest will be linear with an intercept of zero. If CO and unburned hydrocarbons are negligible with respect to CO_2, then the CO_2 concentration represents the fuel-to-product ratio, and the emission index of each species can be calculated from the slope of this line. It has been found that emissions data obtained far downstream in afterburning engine exhaust plumes are approximated well by a straight line but that the intercept is often nonzero.

This linear method was used on the JT8D data of the present study in two forms. First, emission indices for CO and NO_x were determined from a least-squares fit of the data with a nonzero intercept allowed. This procedure is designated as the slope-intercept method. Second, the procedure was repeated to obtain a best-fit regression line with a zero intercept. This method is designated as the slope method. Figure 8 is an example of the slope method showing the regression lines on a plot of NO_x concentration against CO_2 concentration for the Mach 0.8, 9.1-kilometer-altitude tests.

The NO_x and CO emission indices obtained with all four methods are compared in table II. These data show that all methods give nearly identical results. The agreement between the results of the slope method and total-area traverse integration is significant because determining the emission index by the slope method with core-only sampling would require fewer data points, and hence less test time, than would be required to define the emissions profile accurately enough for successful integration.

The integrated total-area average concentrations and emission indices are summarized in table III. Since the engine fuel-air ratio was nearly constant for all tests, the variation of the emission indices with altitude is proportional to the variation in average concentration. Measured values of NO_x emissions decreased with increasing altitude from an emission index of 10.4 to one of 8.3. As altitude increased from 9.1 to 12.2 kilometers, the CO emission index increased from 1.6 to 4.4. Since a CO emission index of 4.27 corresponds to a combustion inefficiency of 0.1 percent, the combustion efficiency for all test conditions was 99.9 percent or greater.

Predicted Altitude NO_x Emissions

The decrease of the NO_x emission index with increasing altitude is shown in figure 9 for all four data reduction methods. Because sufficient refrigerated air capacity was not available, correct engine inlet temperature was not simulated; consequently, the combustor inlet-air temperature for these tests was too high. The corresponding NO_x emissions are therefore higher than would be expected from the engine at the actual altitude and flight speed conditions. Considerable study has been devoted to the correlation of NO_x emissions in terms of the combustor operating variables. With decreased inlet-air temperature, the engine can operate at slightly increased rpm. The effect of reduced combustor inlet-air temperature will therefore be somewhat offset by increased combustor pressure and fuel flow. (Combustor reference velocity will experience negligible change.) However, combustor inlet-air temperature is still the dominant effect.

The major features of the reference 14 correlation were used to correct the NO_x emissions to true altitude conditions. The correction equation used was

$$\frac{NO_{x,alt}}{NO_{x,test}} = \left(\frac{P_{T4,alt}}{P_{T4,test}}\right)^{0.5} \left(\frac{\Delta T_{alt}}{\Delta T_{test}}\right) \exp\left(\frac{T_{T4,alt}/253}{T_{T4,test}/253}\right)$$

where

P_{T4}	combustor inlet total pressure
ΔT	combustor temperature rise
T_{T4}	combustor inlet total temperature, K
alt	true altitude condition
test	actual test condition

The predicted results obtained by correcting the total-area integrated average NO_x emission index to the true altitude conditions are shown in table IV. Figure 9 also shows how the corrected results compare with the uncorrected values from all procedures. With increasing altitude, the correction for inlet-air temperature dominates, and an increasing correction is required. The correction at 9.1-kilometer altitude is of little consequence, while at 12.2-kilometer altitude the NO_x emission index decreased from 8.3 to 7.2.

Sample Validity

The total-area integrated average concentrations were used to compute an average emission-based fuel-air ratio. The ratio of emission-based to metered fuel-air ratios was between 0.88 and 0.92 (table III). Presumably this value would approach 1.0 if a more detailed traverse covering other areas of the exhaust were made. Sample validity values for each test condition are given in table III. Although these values are low for all conditions, they are within the tolerance allowed in reference 13.

Comparison of Results with Predicted Altitude Emissions

As part of the third Climatic Impact Assessment Program (CIAP) conference, Grobman and Ingebo (ref. 16) presented a consensus of estimated jet-aircraft exhaust emissions based on an ad hoc committee study of this problem. The predicted emissions for the JT8D from reference 16 are compared to the test results from this report in table V. Agreement is excellent.

SUMMARY OF RESULTS

Gaseous emissions from a JT8D-109 turbofan engine were measured at nominal cruise throttle setting, over a range of pressure-simulated altitudes from 9.1 to

12.2 kilometers and at pressure-simulated flight Mach numbers of 0.8 and 0.9. Engine inlet-air temperature was a constant 283 K. Detailed profile measurements were made across the horizontal diameter of the engine exhaust nozzle with a single-point traversing gas sample probe.

Emission measurements in terms of volumetric concentration (ppmv) profiles and integrated emission index (g pollutant/kg fuel) gave the following results:

1. Measured values of oxides of nitrogen emissions decreased with increasing altitude from an emission index of 10.4 to one of 8.3 over the range of altitudes investigated. With the aid of correlating parameters the NO_x emission index was corrected for combustor inlet temperature, pressure, and temperature rise to correspond to true altitude operation. This resulted in little change at the lowest altitude, while at the 10.7- and 12.2-kilometer, Mach 0.8 test conditions, the correction decreased the measured values by 1 emission index.

2. Carbon monoxide increased with increasing altitude from an emission index of 1.6 to one of 4.4 over the range of altitudes investigated.

3. Unburned hydrocarbons were essentially negligible.

4. Excellent agreement was obtained between emission indices computed from measurements obtained in the core stream alone and emission indices computed from measurements obtained in the total engine exhaust (core plus fan streams).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 23, 1975,
505-03.

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TABLE I. - ENGINE TEST CONDITIONS

Simulated altitude, km	Mach number	Engine inlet total pressure, N/cm^2	Combustor inlet-air temperature,[a] K	Combustor inlet total pressure, N/cm^2	Total fuel-air ratio[b]	Bypass ratio
9.1	0.8	4.59	663	66.2	0.00429	2.34
10.7	.9	4.05	658	56.9	.00420	2.38
10.7	.8	3.65	661	51.9	.00430	2.37
12.2	.8	2.87	652	39.3	.00423	2.43

[a]Engine inlet-air temperature 283 K for all conditions.
[b]ASTM D-1655 aviation turbine fuel, Jet A. Computed from metered fuel flow and total engine airflow (core and fan).

TABLE II. - COMPARISON OF FOUR METHODS FOR COMPUTING EMISSION INDEX

Cruise condition		Carbon monoxide emission index				Oxides-of-nitrogen emission index			
Altitude, km	Mach number	Integrated		Slope-intercept method	Slope method	Integrated		Slope-intercept method	Slope method
		Total area	Core			Total area	Core		
9.1	0.8	1.6	1.6	1.9	1.8	10.4	10.3	10.4	10.4
9.1	.8	2.8	2.7	2.6	2.8	10.2	10.2	10.0	10.2
10.7	.9	2.7	2.8	2.9	2.8	10.3	9.8	9.8	10.0
10.7	.8	3.9	3.8	3.6	3.8	9.2	9.2	9.4	9.3
12.2	.8	4.4	4.2	4.2	4.3	8.3	8.3	8.5	8.4

TABLE III. - SUMMARY OF TOTAL-AREA INTEGRATED EMISSION DATA

Cruise condition		Carbon dioxide		Carbon monoxide		Oxides of nitrogen		Sampling validity[a]
Altitude, km	Mach number	ppm	Emission index	ppm	Emission index	ppm	Emission index	
9.1	0.8	8179	3145	6.6	1.6	25.9	10.4	0.925
9.1	.8	8158	3128	11.5	2.8	25.4	10.2	.918
10.7	.9	7685	3144	10.5	2.7	24.1	10.3	.887
10.7	.8	7817	3142	15.4	3.9	21.8	9.2	.881
12.2	.8	7768	3141	16.9	4.4	19.7	8.3	.891

[a]Ratio of emission-based to metered fuel-air ratio.

TABLE IV. - OXIDES-OF-NITROGEN

TOTAL-AREA INTEGRATED

EMISSION INDEX

Cruise condition		Oxides-of-nitrogen emission index (integrated, total area)	
Altitude, km	Mach number	As measured	Corrected
9.1	0.8	10.4	10.3
9.1	.8	10.2	10.0
10.7	.9	10.3	9.7
10.7	.8	9.2	8.1
12.2	.8	8.3	7.2

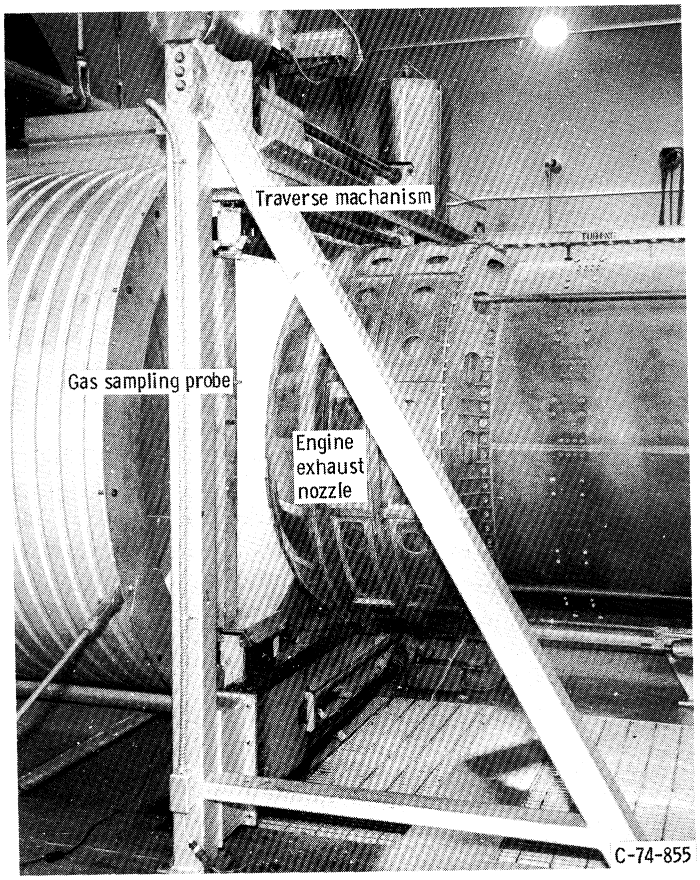
TABLE V. - COMPARISON OF EXPERIMENTAL

EMISSION INDEX DATA WITH PREDICTED

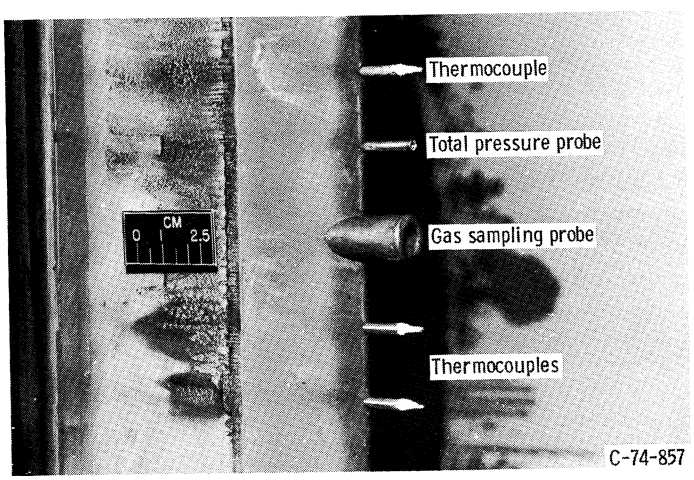
DATA FROM REFERENCE 17

Emission	This report		Reference 17
	10.7 km; Mach 0.8	12.2 km; Mach 0.8	
Oxides of nitrogen[a]	8.1	7.2	6 - 8
Carbon monoxide	3.9	4.4	4.0
Unburned hydrocarbons	---	---	.1

[a]Corrected to true altitude conditions.

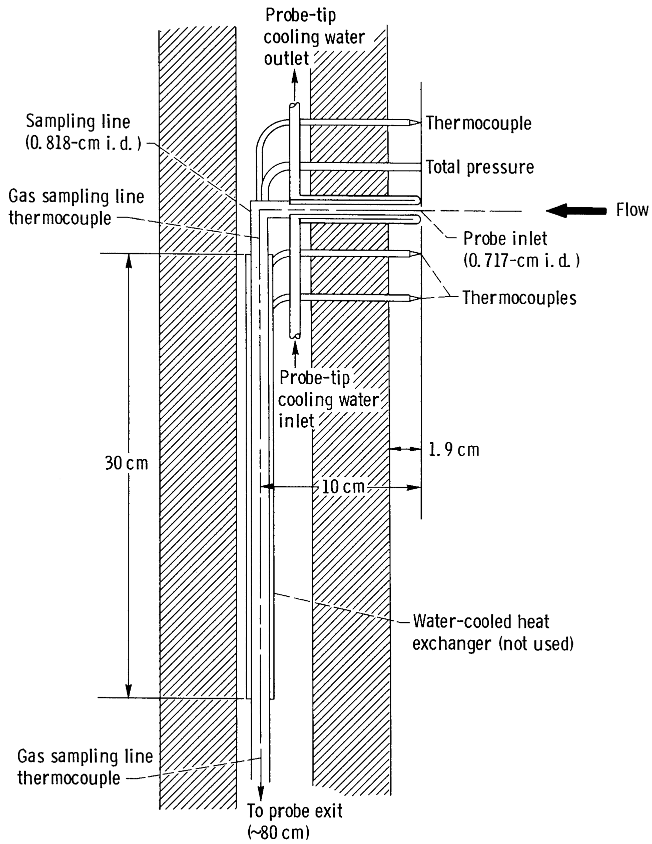


(a) Probe and traversing mechanism.

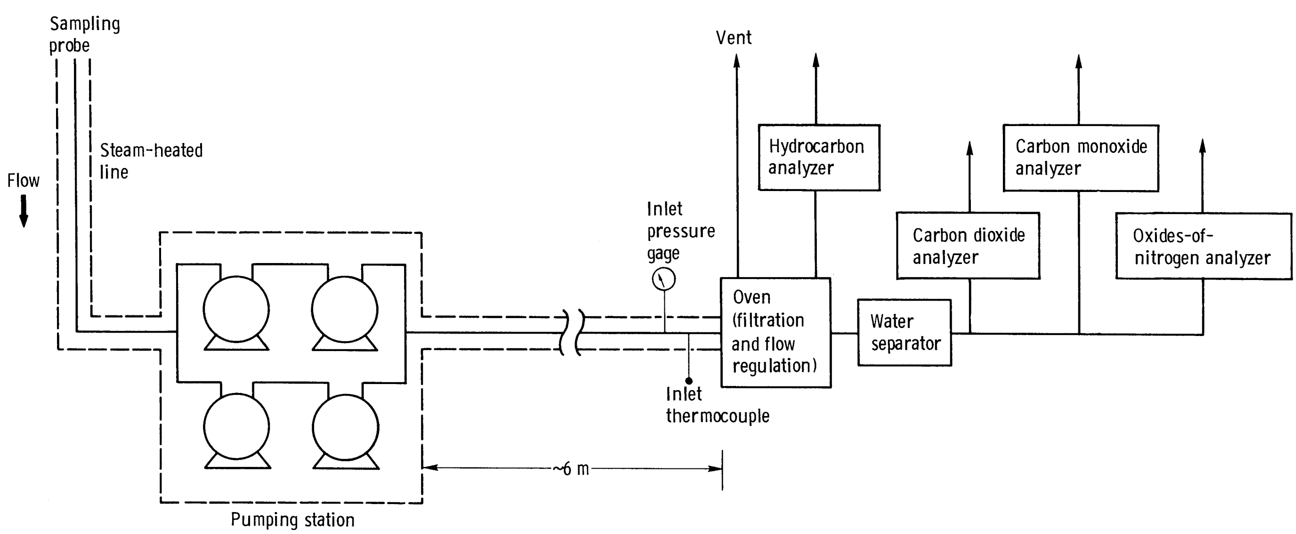


(b) Detail of sensor area.

Figure 1. - Gas sampling probe.



(a) Schematic of gas sample probe.



(b) Flow diagram of system.

Figure 2. - Exhaust gas analysis system.

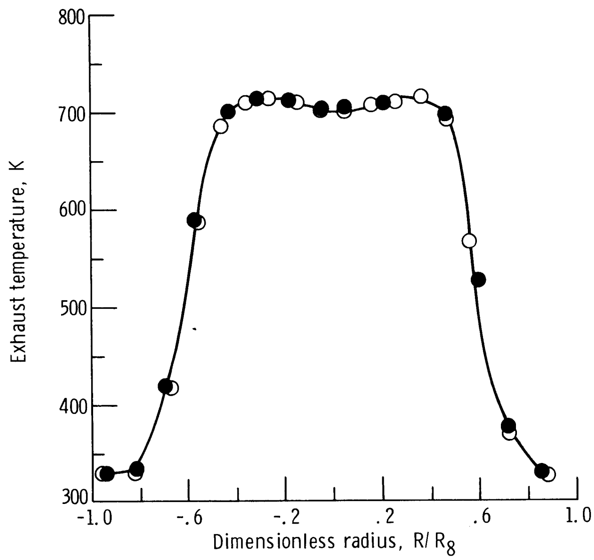


Figure 3. - Exhaust temperature profile. Pressure-simulated altitude, 9.1 km; Mach 0.8. Open and solid symbols indicate duplicate data taken on different test dates.

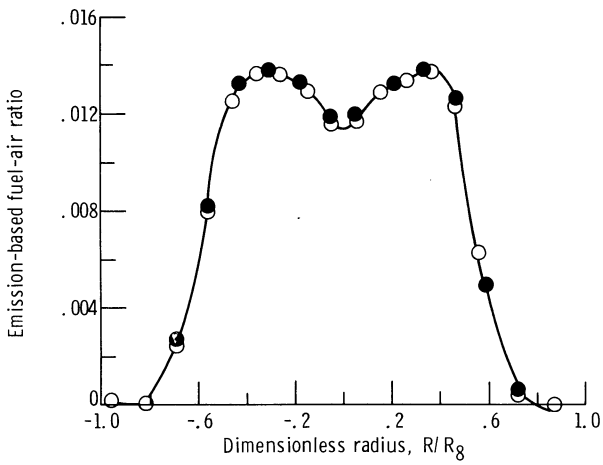


Figure 4. - Fuel-air ratio profile. Pressure-simulated altitude, 9.1 km; Mach 0.8. Open and solid symbols indicate duplicate data taken on different test dates.

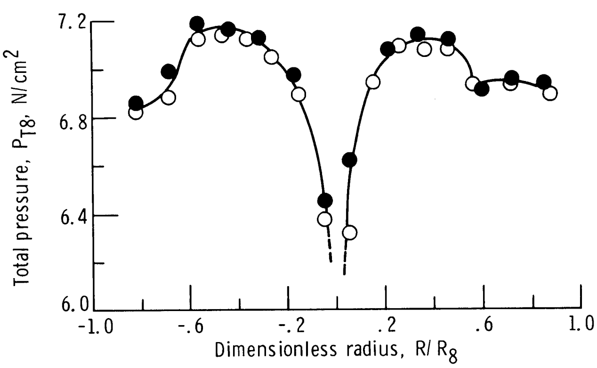


Figure 5. - Total pressure profile. Pressure-simulated altitude, 9.1 km; Mach 0.8. Open and solid symbols indicate duplicate data taken on different test dates.

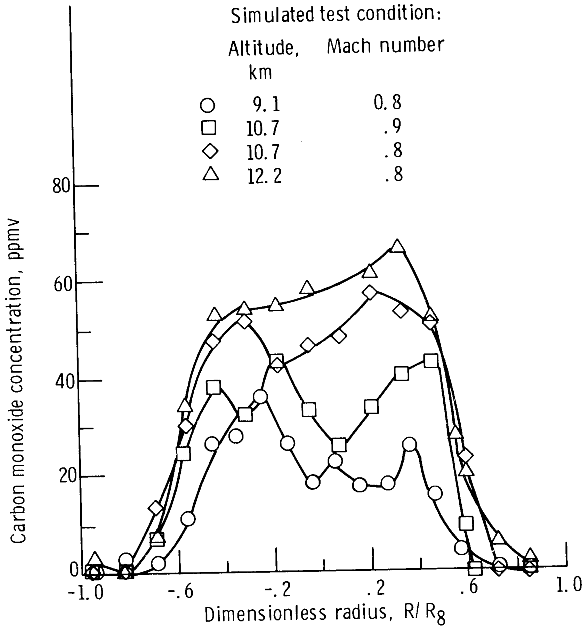


Figure 6. - Carbon monoxide profiles.

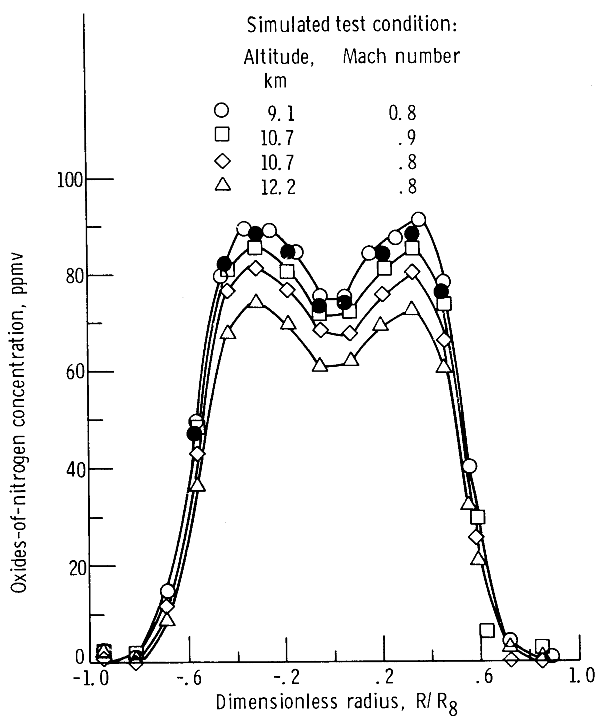


Figure 7. - Oxides-of-nitrogen profiles. Open and solid symbols indicate duplicate data taken on different test dates.

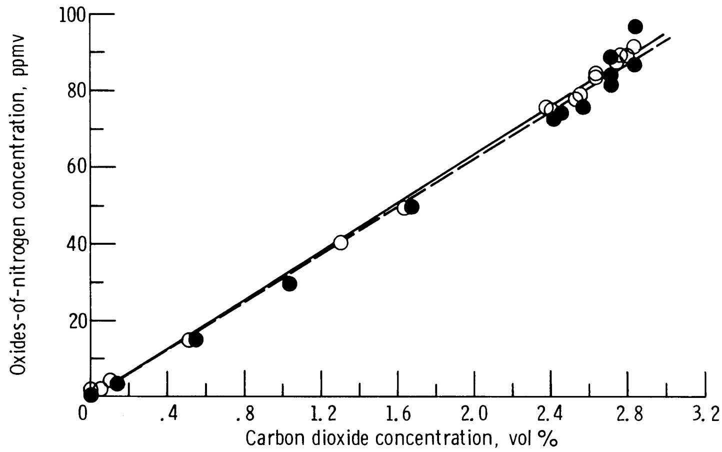


Figure 8. - Best-fit lines for slope method of computing emission index for oxides of nitrogen. Pressure-simulated altitude, 9.1 km; Mach 0.8. Open and solid symbols indicate duplicate data taken on different test dates.

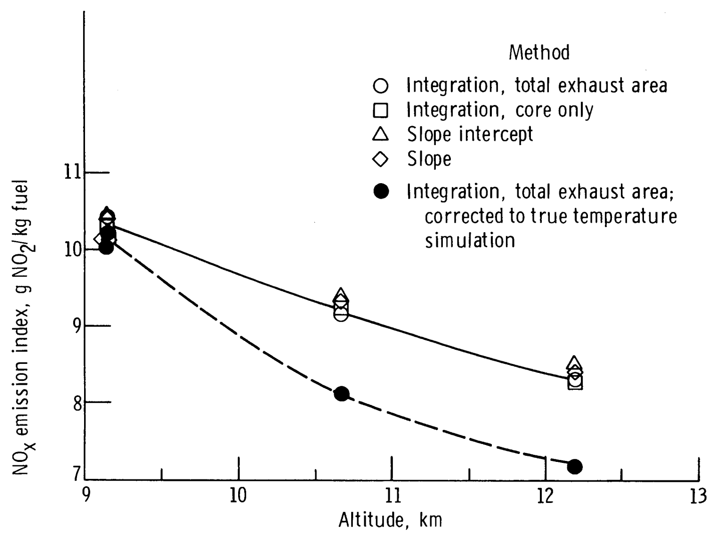


Figure 9. - Effect of altitude on oxides-of-nitrogen emission index at Mach 0.8.

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